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13. ABSTRACT (Maximum 200 words)

This report discusses a Broadband Bionic Sonar System and a signal processing technique for detection and identification of underwater targets. Since the sonar and radar target echoes are the solutions to the same Helmholtz Equation in their respective media, an Ultra Wideband Radar System can also be developed for target detection and identification base on the same principles and signal processing techniques. In the bionic sonar system with the resonance detection technique for detection and identification of underwater targets, it appears to mimic a dolphin's and/or a bat's acoustic sensory systems. It is onceivable that an Ultra-Wideband Radar System of the same detection technique can also be developed.

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Broadband (Ultra Wideband) Sensor System for Active and Passive Detection and Classification of Targets

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Introduction

This report discusses a successful investigation of a Bionic Sonar System and a signal processing technique for detection and identification of underwater targets. The Bionic Sonar System is a broadband sonar system which seems to mimic a Dolphin's sensory system. Based on the data collected and evaluated, it appears to concur with the Resonannt Scattering Theory. That is, that all objects and/or cavities resonate at their natural frequencies characteristic to their sizes, shapes, structure and material compositions. Employing a correlation signal processing algorithm (G-Transform) for the detection of resonance and a neural networks for target recognition, a Bionic Sonar System for active and passive detection and identification of underwater targets has been successfully demonstrated.

The dolphin's sonar system transmits a very short broadband pulse. It detects and classifies a target by processing the modulation of the echo's (back scattering) broadband spectrum. This spectral modulation is directly related to the target's natural resonance. Using the G-Transform, a correlation technique, the author has shown that target resonance exists and is detectable. This resonance is unique to the target's size, shape, structure and material composition in the G-Transform domain. Furthermore, this natural resonance exists both actively in the acoustic back scattering from a target and passively in the acoustic scattering from a target in acoustic noise background. Using a "trained" adaptive neural networks, these targets' resonances/signatures can be correctly identified for the respective targets with high degrees of accuracy.

A variety of experimental results over the past decades indicates that dolphins possess a highly sophisticated broadband sonar system. For many years, Au, Goo, and others have reported dolphin-like capabilities in identifying targets based on sizes, shapes and material compositions. It was shown that this broadband sonar is highly adaptive in detecting, discriminating and recognizing objects in a reverberating and noisy acoustic environment. It was also demonstrated and reported that bionic

sonar can detect and identify targets on the bottom of the water and targets buried in the mud. In addition, recent experiments using the same detection technique indicate that underwater targets are detectable and identifiable in "acoustic daylight" or acoustic background noise or just acoustic noise. These results confirm that underwater targets are not only detectable and identifiable in acoutic background noise, but also the bottomed (prone) targets on the ocean floor and the buried targets in the mud. This seems to suggest that the dolphin's approach to target detection and recognition is based on resonance and resonant scattering of these targets. Most importantly, this target resonance exists in both active and passive sonar environments. This broadband detection method based on Natural Resonance and Resonant Scattering Theory was presented at SPIE Conferences for the past few years[9-14]. Using the G-Transform, acoustic echoes from different sized, and shaped targets have unique transformed signatures. These unique signatures were used as inputs to "train" a neural networks for target detection and recognition. After "training", the "trained" neural networks have demonstrated their superior capability in detecting and identifying underwater mine and minelike targets. This paper is divided into six parts. Part II presents the dolphins' bionic sonar system. Part III describes the G-Transform, its purpose and its usefulness in presenting the unique characteristics of targets. Part IV defines resonance and resonant scattering. Part V describes the active and passive experimental results of target detection and identification. Part VI presents the results and conclusions.

Bionic (Dolphin) Sonar System

Dolphins possess a unique sonar system. It was reported that the dolphin's head serves as an acoustic lens[1]. The transmitted pulse is focused to a narrow beam of approximately twenty (20) degrees as it passes through the head of a dolphin. The dolphin transmits a very short sinusoidal like pulse as diagrammed in figure 1-a. It is only 50 micro-seconds long. The frequency composition of the transmitted pulse is a broadband signal centered at 120kHz as diagrammed in figure 1-b. Figure 1-c is the "Phi" domain representation of this transmitted pulse. Figure

1-d is a 3-D, time-frequency presentation of this transmitted pulse. It is a short-time FFT of a sliding window of 30 micro-seconds long of the transmitted pulse of figure 1-a. It is interesting to note that the frequency content of each of the sliding windows is the same. In other words, the transmitted pulse is a broadband pulse at all times. Careful examination of figure 1-d indicates that the energy level is also constant over the entire pulse. Figure 1-e is the "phi" domain presentation of the transmitted pulse. The dolphins analyze the return echoes or back scattering from the targets. From figure 3, one can observe the variations in time domain and "phi" domain presentations of four typical echoes from four cylinders. These open ended cylinders are of the same size and same wall thickness but made of different materials - steel, aluminum, bronze and glass. Dolphin experiments have shown that these variations can be differentiated by the dolphins even when background noise is added to the echoes. Theoretically, the variations in the four resonance signatures result from the different materials of these targets. These resonances are directly related to the scattering solution of the Helmholtz Equation as reported by many authors in the references. Thus, possibly, dolphins are able to detect and identify targets by resonance.

Resonant Radiation & "G" Transform

Based on 17 of the 22 references, it is clear that underwater targets respond to acoustic excitation. It appears that underwater targets respond to narrow band frequency excitation as shown theoretically by Gaunaurd, Uberall, etc.[8] and experimentally demonstrated by Tsui and Reid[16]. These narrow band frequency responses show that the targets resonate at the nulls of these frequency spectrums. Targets also respond to broadband frequency signals[10-14]. These responses appear as modulations on the frequency spectrums of the echoes. These resonant responses also appear as nulls on the broadband spectrum. Some of the authors[2,5,21,22] show this resonant modulation as nulls in the wave numbers. In the case of a dolphin sonar, these resonant responses appear as modulations to the transmitted spectrum[1,10-14]. Thus, the target interacts with each frequency component in the band differently. Since

target resonance is determined by its dimensions, shape, material composition, and structure, the frequency modulation is unique to the target in terms of size, shape, material, etc. Thus, characteristic information about a target appears in the spectral domain of the target's echo. G-Transform was found to be a simple and efficient process to present this information as shown by the author[10-14]. Mathematically, G-Transform is a triple forward Fourier Transform of time signal, S(t), as shown in equation (1) below:

$$\mathbf{S}(\ \varphi\ ) = \mathbf{FFT}\ \{\ \ \mathbf{FFT}\ [\ \mathbf{FFT}\ (\ S(t))\ ]^{\,2}\ \}^{\,2}\ . \qquad (1)$$

But, S(w) is the Fourier transform of the S(t) which is:

$$S(w) = \mathbf{FFT}\ (\ S(t)). \qquad (2)$$

Therefore, $S(\varphi)$ can be written as

$$\mathbf{S}(\ \varphi\ ) = \mathbf{FFT}\ \{\ \ \mathbf{FFT}\ [\ S(w)\ ]^{\,2}\ \}^{\,2} \qquad (3)$$

or $S(\varphi)$ is the auto-correlation of the **[** S(w) **]** below:

$$\mathbf{S}(\ \varphi\ ) = \textbf{Auto-Corr.}\ \{\ [\ S(w)\ ]\ \} \qquad (4)$$

From mathematics, the auto-correlation of a time domain signal, S(t), is "tau" domain, $S(\tau)$. Then, the auto-correlation of a frequency domain signal, S(w), was named "phi" domain, $S(\varphi)$. If Cepstrum is defined as the Fourier transform of the Auto-Correlation of the time signal, S(t), then G-Transform may not be Cepstrum. Then, possibly, G-Transform is a modified Cepstrum of the time signal, S(t).

Why the G-Transform? Studies[10] show that a time echo, S(t), from a target varies from echo to echo. Even consecutive echoes from the same target are different. Thus the Fourier Transform of these echoes also varies from echo to echo. However, in the "phi" domain, $S(\varphi)$, these consecutive echoes from the same target remain the same. Thus, in the

"phi" domain, targets have unique signatures based on the target's size, shape, etc. Using a trained Back-propagation Neural Networks[9] with 30-input nodes, 8-hidden layer nodes and four (4) output nodes and over 500 test target echoes for each aluminum, bronze, glass, and steel cylindrical targets, no error was detected.

Resonance and Resonant Scattering

Over the past decades, many broadband (dolphin) sonar experiments have been conducted demonstrating that dolphins possess a superior sonar system. They can detect, discriminate and recognize object structures, shapes, sizes and material compositions with 85-90% accuracy. Other animals such as blue whales, seals, and bats also possess unique biological sonar systems which are highly adapted to their environments. Using their sonar systems, these sea mammals can range and identify characteristics of submerged objects by transmitting a broadband signal and processing the returned echoes from these objects[1]. Using trained neural networks to recognize these target echoes in the frequency domain, bionic sonar systems mimicking these mammals were designed and successfully demonstrated. These systems have performed as well as the dolphins can, that is 85-90% accuracy. However, exactly how these mammals detect and identify targets is still a mystery.

The scattering theory of structures has been investigated[3-8,16-19] for many decades. These studies have resulted in the theoretical development of scattering of elastic spheres in liquid[21] and ray trace technique[22]. The authors simulated the acoustic echoes from an elastic smooth shell in water. Using the Ray Trace technique, they contributed to the understanding of the mechanism of this elastic wave propagating in an elastic shell. They also contributed to the understanding of radiation or scattering of this acoustic energy from the shell to surrounding media. In this paper, this radiation from the elastic shell is referred to as resonance and resonant scattering. A collaborated investigation with Yang showed perfect concurrence of the measured data with the calculated exact solution of a dolphin acoustic echo from a 3-inch air-

filled, 24 gage, stainless steel sphere. In this study, a dolphin acoustic echo, figure 2-a, contains the two components which can be separated into the specular reflection component, figure 2-c, and the resonant or back scattering component, figure 2-b. In an acoustic echo, the frequency composition of a resonant scattering component is different from the frequency component of a reflection component as shown in figures 2-e and 2-f, respectively. Although they are of the same band width (same as the transmitted bandwidth), the modulation on their frequency spectrums is different. In figure 2-f, the frequency spectrum of the specular reflection is identical to the transmitted signal. Figure 2-e shows a strong modulation of the spectrum of transmitted signal. One observes that specular reflection, figure 2-j, is the same as the G-Transform of the transmitted signal. Whereas, figure 2-h shows the resonant component with a unique characteristic signature. From Yang's Ray Trace simulation, the resonant component is the same back scattering energy radiated from the air-filled steel spherical shell into the water. Furthermore, the spectral modulation in figures 2-d and 2-e are identical to predicted waveforms of Flax's paper on "Theory of Resonance"

Active and Passive Acoustic Experiments and Results

Active Acoustic Experiments

The active sonar experiments were conducted in a 10-foot diameter tank. A broadband acoustic transducer is suspended near the center of the tank, while, the test targets are located a meter in front of the transducer. The transducer transmits a dolphin's broadband pulse toward the target. It then receives the return echo from the target. After some signal conditioning, the target echo was digitized at 1MHz and recorded in a computer memory. Figure 3 are typical echoes of glass, steel, bronze and aluminum cylindrical targets about 2.5 inches in diameter, 4 inches in length and 7/32 inch in wall thickness. From figure 3, one can observe the differences of the echoes in time domain signal and in the G-Transformed "phi" domain signal. One can observe in the references the uniqueness of these signatures[11-13] due to target shapes, sizes and materials. Using a

"trained" neural networks, Au and other authors have shown that it can identify these targets as well as a dolphin can. In the bionic sonar system, time domain echoes were G-Transformed into "phi" domain signatures (signals) as shown in figure 3. The noise free transformed signature is then processed by the trained neural networks to identify the signature. In our neural networks' training process, all noise free signatures from each target al all angles of 5-degree increments were used in the training process. In other words, neural networks will only learn the correct signatures from all measured angles (only one signature was given for each target at 5-degree increments). In testing the neural networks, the noise free and noisy signatures were used for testing. Of course, when the noise free signatures were used for testing the results were always 100% correct. However, when noisy targets were used the results were dependent on the amount of random scattering noise added to the echoes.

In an active sonar system such as the bionic sonar, the scattering noise in the water is not totally statistically independent. It is correlated to the transmitted pulse. In the case of the dolphin bionic sonar, the transmit pulse is the dolphin transmission as shown in figure 1-a. Thus, for the dolphin bionic sonar, the scattered noise is generated by convolving the dolphin transmitted time signal with the Gaussian random impulses. From NCSC studies, this is a good representation of the scattering noise in an active sonar system. In addition, the method for scaling the signal-to-noise ratio (SNR) is given as

$$SNR(in\,Db) = 20 * \log_{10}\left(\frac{|\text{ Peak amplitude of Signal }|}{1.414*(\text{rms of reverberation})}\right) .$$

Having added the scaled noise to the target echoes, the time signal is then G-Transformed into "phi" domain signatures. An adaptive neural networks was used for target identification. The signatures in the right column of figure 3-a are noise free, phi domain signatures of the four cylindrical targets. The amplitudes of these signatures were first normalized. Then, the first 202 data points of each signatures were used as inputs to the

neural networks' input layer for identification. The neural net's middle (hidden) layer has 12 nodes; while its output layer has four nodes, one for each of the targets. In the dolphin bionic sonar system using the above adaptive neural networks, figure 4 shows the capability of the bionic system in identifying the four same sized cylindrical targets of different materials in background noise. The results range from 100% correct at 20Db, SNR ratio, to 99.5% at 12Db, 96.25% at 10Db, and 65% at 3Db SNR ratio. Similarly, figure 3-b showed the time domain chirp echoes and the G-Tansformed signatures of these echoes of the six standard targets with broadband "chirp" data from NCSC, Panama City. A larger neural networks was used. Using the same noise addition process, scattering noise was added to the echoes. The noisy echoes were then G-Transformed into phi domain signatures for identification. For the bat bionic sonar, the neural networks has 256 inputs at the input layer, 38 nodes in the middle layer, and 6 output nodes at the output layer. From the results in figure 4, a 100% accuracy was obtained from the 20Db SNR ratio test data. An accuracy of 96.5% was obtained at 12Db SNR ratio. If the targets were partitioned between man-made vs. non-man-made targets, then the bionic sonar correctly identified the targets to an accuracy of 98.8%. Base on these results, it appears that the present straight forward G-Transform process did not work as well for the "chirp" signal as for the dolphin signal. In the future, we will consider doing the training with data collected at even aspect angles and the testing with odd aspect angles, as other ONR researchers have. This is a preferred training and testing process, which will provide ONR a better evaluation of our approach. However, the training process, used in this paper, does demonstrate feasibility of our approach.

Passive Acoustic Experiments

Background noise[3], also referred to as "acoustic daylight", exists naturally in open water. This background acoustic noise is background acoustical energy. As described by Buckingham and his co-authors, the noise is generated by wave action against the shores, the beaches, the rocks, and the collapse of air bubbles in the breaking waves (white caps)

created by wave motion. Furthermore, acoustic noise is generated by ships at sea and motor boats in the harbor. In addition, noise can also be generated by sea animals such as whales, dolphins, snapping shrimps, etc. Acoustic noise energy is equivalent to light being reflected from walls, ceilings, and objects around us into our eyes that enables us to "see". Thus, one can image underwater[3,19] with background noise. Dr. Yang's simulation suggests that underwater object illuminated by a transmitted pulse will radiate, back scatter, at its natural resonant frequency. Thus, if a target is illuminated by background noise, it will also radiate at its natural resonant frequency. Therefore, underwater objects can be detected by its resonant radiation in background noise. Since no pulses were transmitted, the system is a passive sonar system. The system just "listens" for the object resonance in the background noise. Technically speaking, the signal processing algorithm is to detect the presence of resonant signals in the noise. In the many experiments during the past two years, many detectable resonant signals were recorded and detected with the bionic sonar algorithm. Visually, one can observe the different signatures between a cylinder and a sphere and the difference between solid sphere vs. air-filled spheres.

The passive experiments were conducted on a 10' X 20' floating platform (a floating dock) in one of many coves off Coconut Island in Kaneohe Bay, HI. The cove faces the inside of the bay where there is no direct shipping noise into the cove from the open waters. Most of the noise is generated by wave action against the rocks and shoreline in the bay. There were occasional noises from snapping shrimp and dolphins. Many experiments were conducted on the edge of the deck with a "SonoPanel", a broadband planar acoustic sensor. A 2.5 inch diameter aluminum cylinder, and a 3 inch, a 6 inch, and a 12 inch diameter stainless steel sphere targets were placed in front of the sensor for these noise measurements. Measurements were recorded before and after each cylinder was placed in front of the sensor. Results were recorded and processed. Figures 5 & 6 are diagrams of these detectable resonances of a 3-inch solid brass sphere and a 2.5-inch diameter aluminum cylinder in the background noise. It is clear that some resonant scattering was present and these natural resonance corresponded to the characteristics

of these targets. In a recent experiment, the resonance from the same 3 inch diameter air filled stainless steel sphere was detected in three conditions: when the sphere was suspended in the water, when the sphere was placed (prone) on the muddy bottom of the water, and when the sphere was buried in the muddy bottom. These results are presented in figure 7, 8 and 9, respectively. From these plots, clearly some resonant signatures exist in the acoustic noise environment.

Conclusion

Having extensively investigated the broadband (dolphin) sonar system, it appears that there are many advantages to a broadband system over a narrow band system. In an active sonar system, the broadband system can echolocate a target equally as well as any conventional narrow band system. From our study and Yang's simulation, it is clear that the target echo contains two parts: the specular reflection and the back scattering. The specular reflection is the mirror image of the transmitted signal which is the stronger part at the beginning of the return echo. This is very useful in echolocation. The back scattering part contains the characteristics of the target in the form of modulations on the transmitted broadband spectrum. These modulations on the broad frequency spectrum are attributed to target shape, size, structure and material composition. This frequency modulation appears to be the natural resonance of the target as shown in Yang's computer simulation. Based on the success in background noise experiments, this frequency modulation also exists in a passive broadband sonar system where the illuminator is the background noise, "Acoustic Daylight". A different modulation on the background noise spectrum was observed between spheres and cylinders. In addition, a different modulation on the noise spectrum were observed between hollow spheres and solid spheres. This seems to indicate that underwater targets resonate at their natural frequencies. Since these frequency modulations are unique to the targets, the transformed signatures of these modulations are also unique to the targets. Thus, these transformed target signatures can be used as input to a "trained" neural networks for target recognition/identification.

From the study, it is clear that the broadband (dolphin) sonar system has many advantages over the narrow band system and the "chirp" wideband system. They are:

1. equally effective in target echolocation,

2. superior in target identification,

3. superior in detecting and identifying a target in a noisy environment,

and 4. consistently capable in detecting and identifying a target in "acoustic daylight", acoustic background noise.

The ability to detect a target in background noise is vital in underwater surveillance and harbor security. Conversely, a "bottomed" submarine is no longer safe because it is detectable in background noise. Furthermore, Baum[2] and Gaunaurd and Uberall[7] showed that a broadband sonar echo is similar to that of a radar echo. Mathematically, these echoes are solutions to the Helmholtz Equation in a different media. Thus, the technique for broadband sonar target detection and identification can easily be adapted to a broadband radar system. Most importantly, as suggested in Baum[2], a library of target aspects to a radar system can be developed for target identification using pattern recognition techniques or neural networks. It is true that the sonar echoes and radar echoes are solutions to the same Helmholtz Equation in two different media; then similar to acoustic daylight, there exists microwave (radar noise) daylight in the atmosphere due to natural and man made sources. These man made sources can be radio and TV station transmissions, cell and cordless phones transmissions, local and military microwave transmission systems, other communication and radar systems transmissions, etc. The existence of radar noise is obvious; therefore, it is conceivable that a passive bionic radar system for target detection and identification can also be developed.

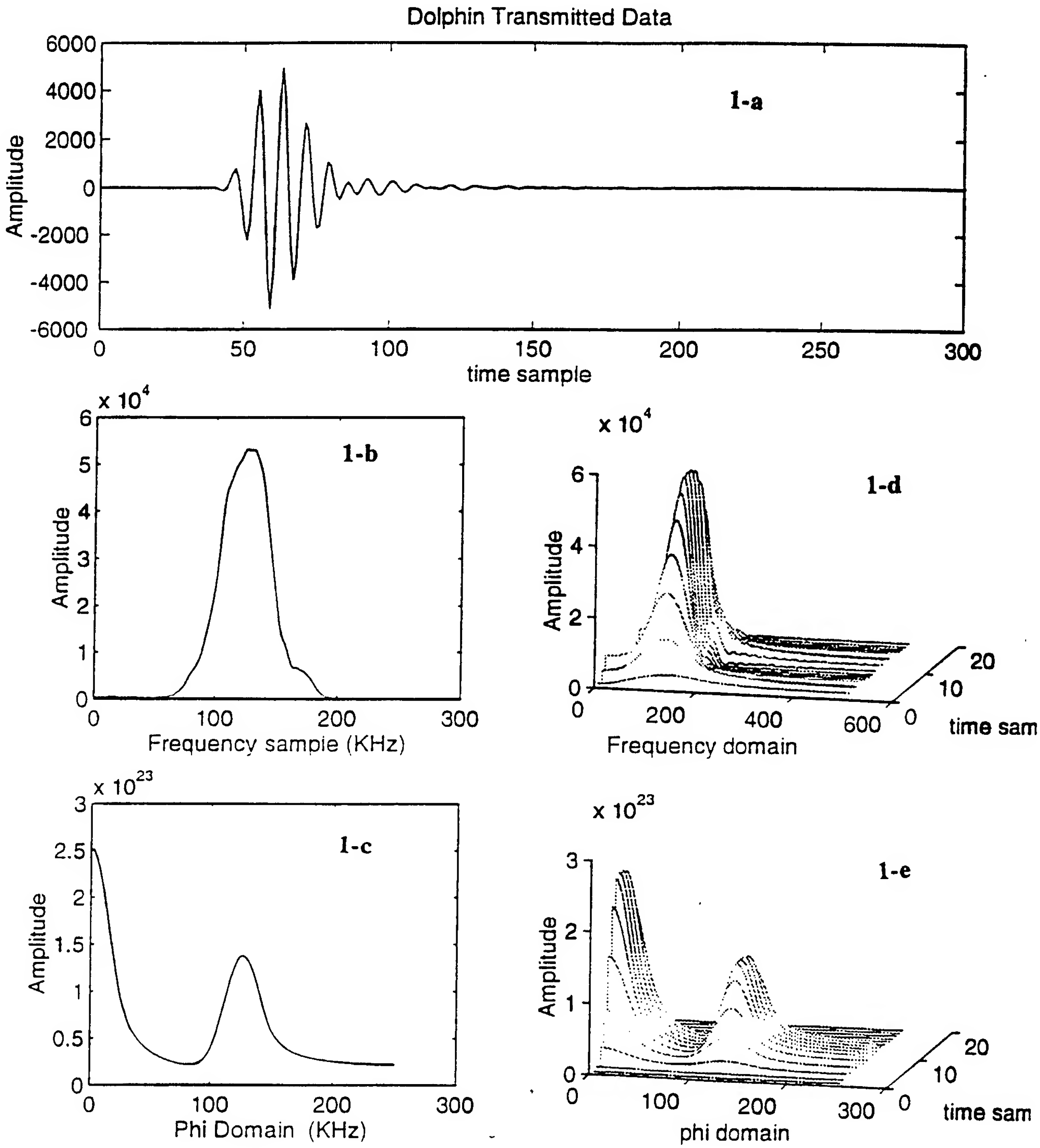

Figure 1. Transmitted Dolphin Pulse

Scattering of 3-inch Air Filled Stainless Steel Sphere

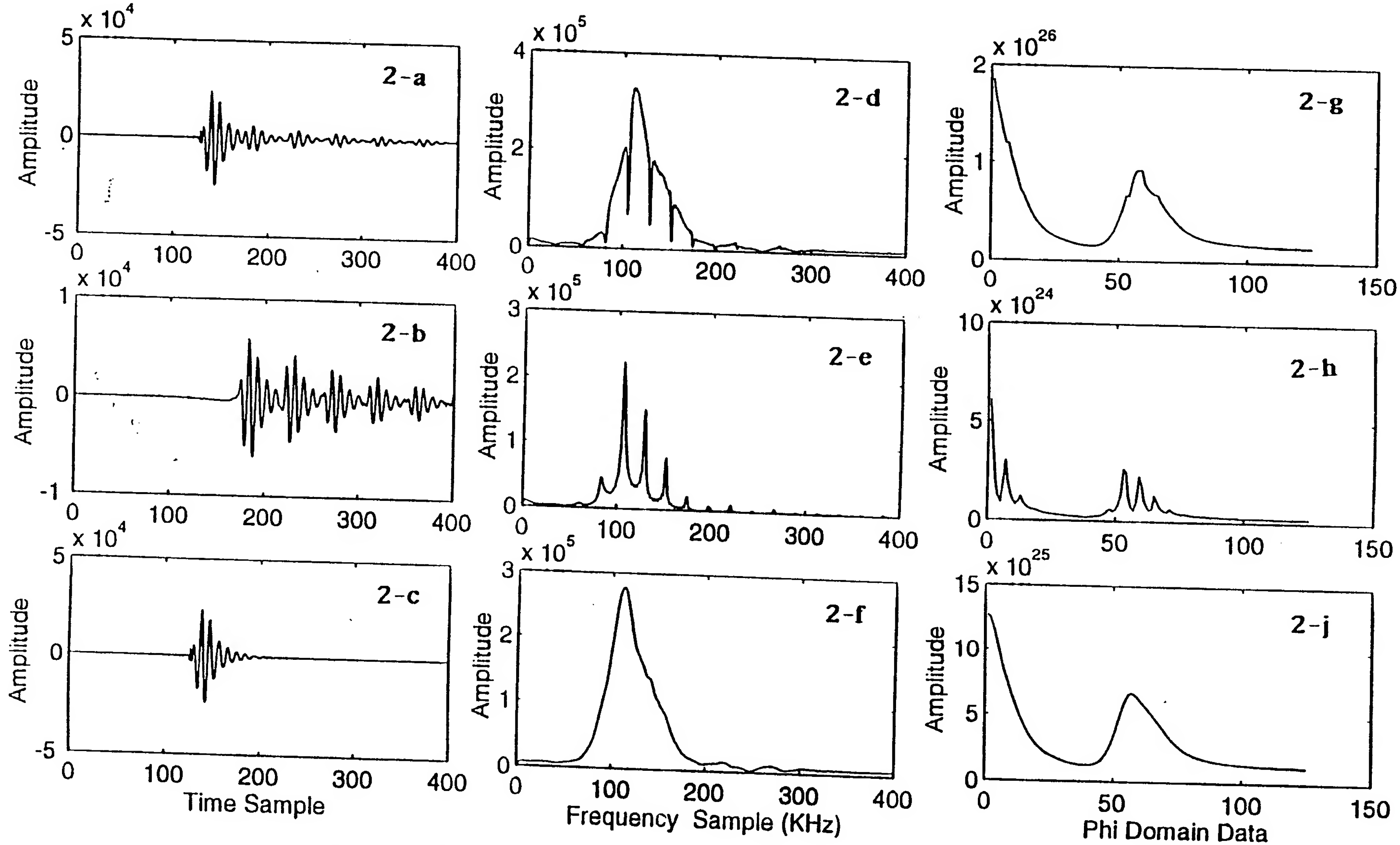

Figure 2. Echo, Scattering and Specular Reflection

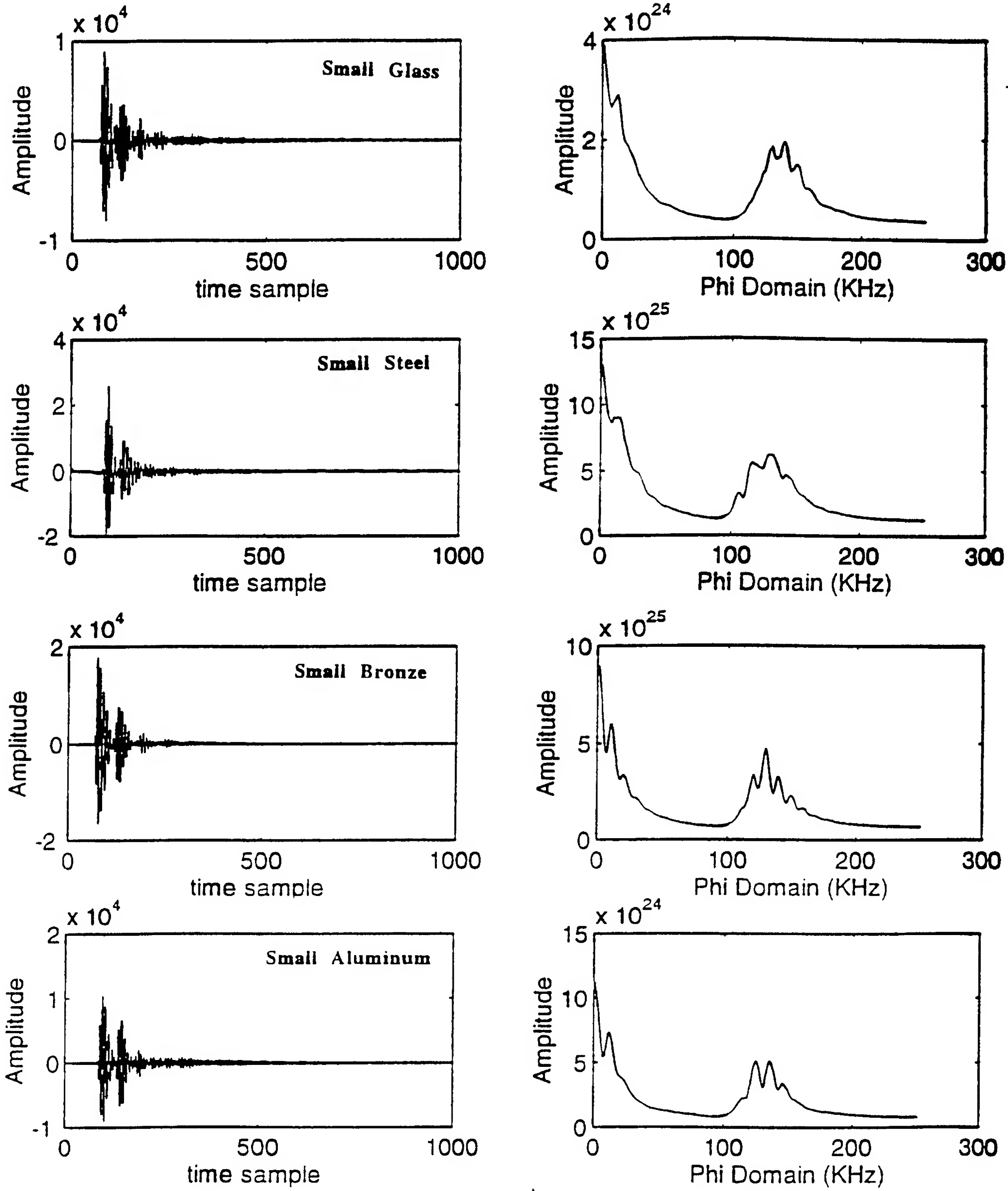

Figure 3a. Typical Small Cylinder Target Echoes and Signatures

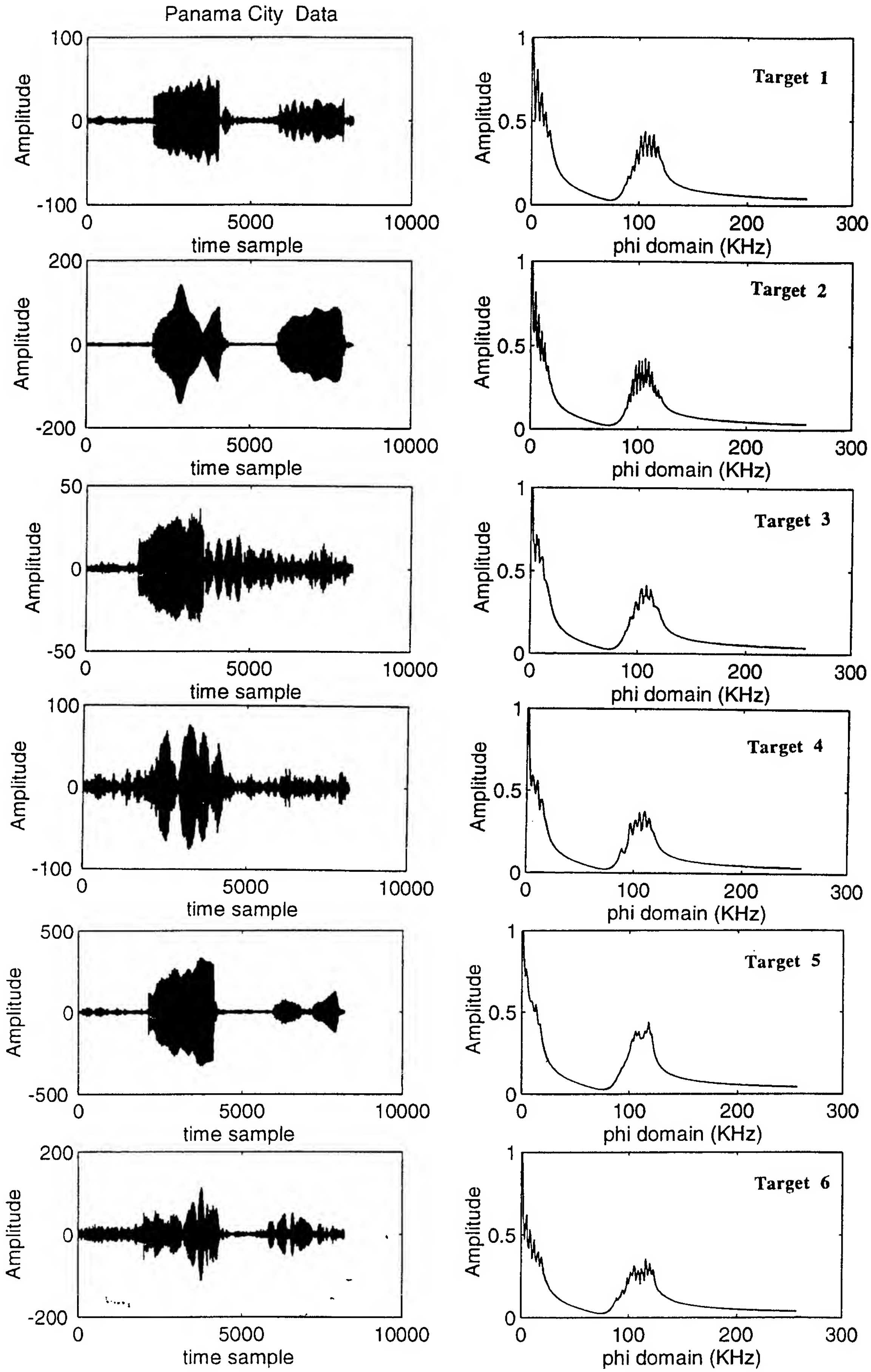

Figure 3b. Typical NCSC Standard Target Echoes and Signatures

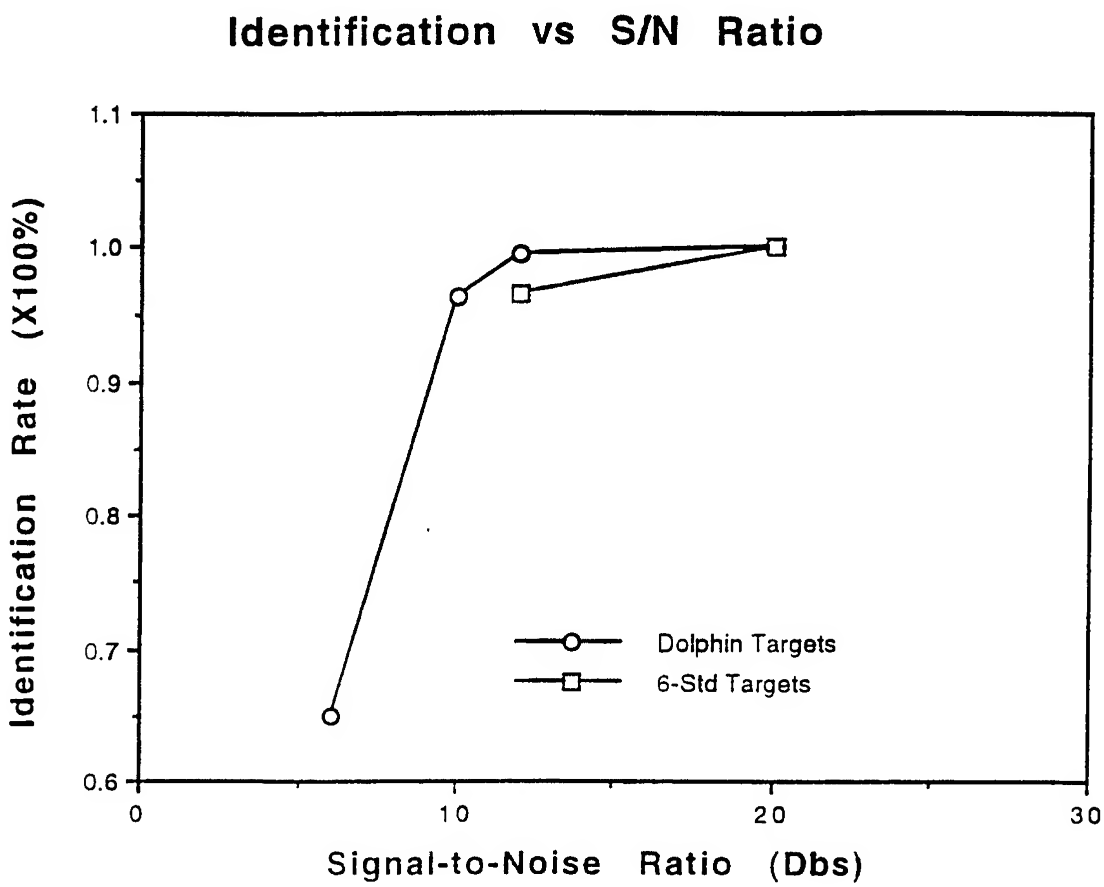

Figure 4. Indentification vs. Signal-to-Noise Ratio

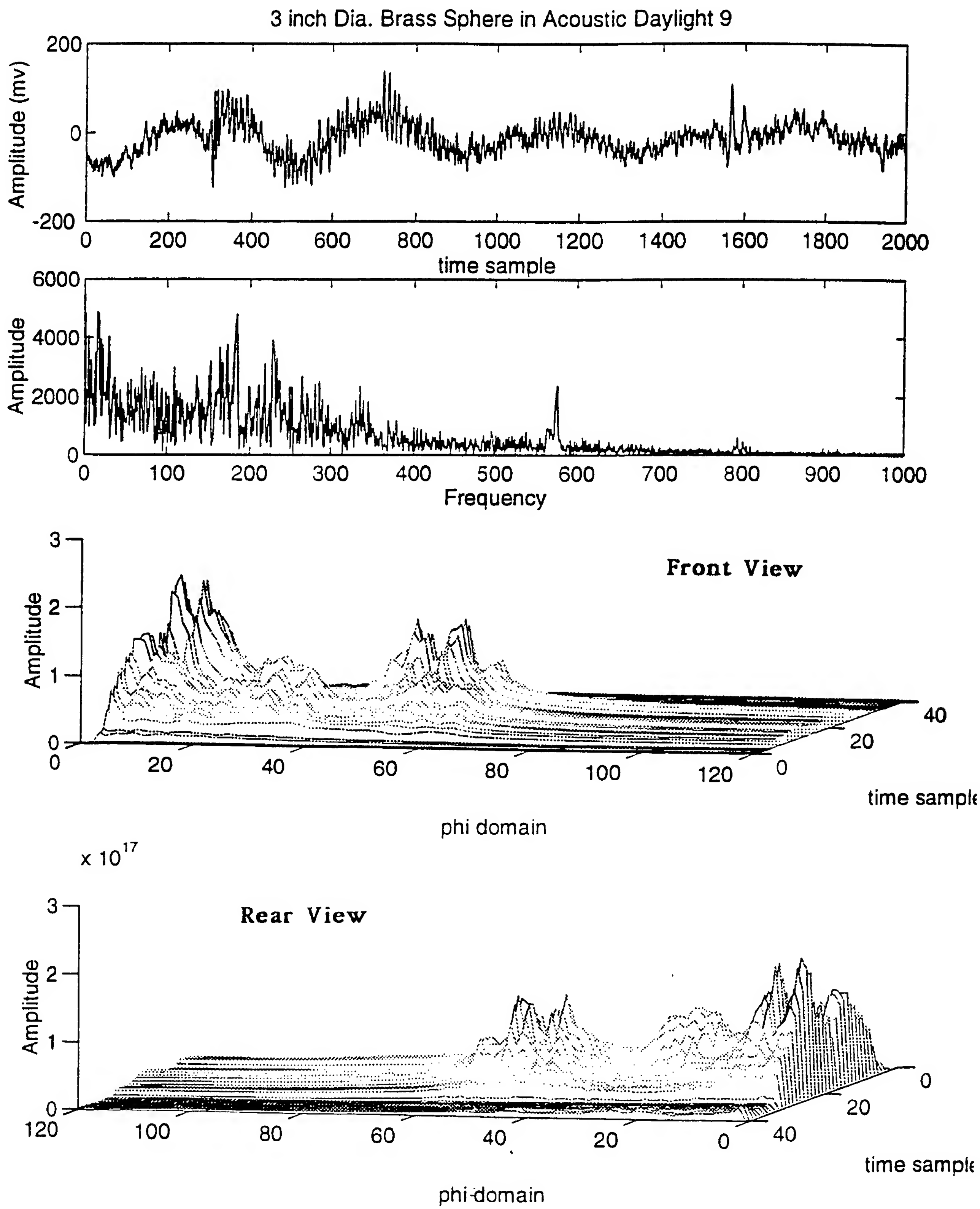

Figure 5. Scattering of a 3" Solid Brass Sphere in Acoustic Background Noise

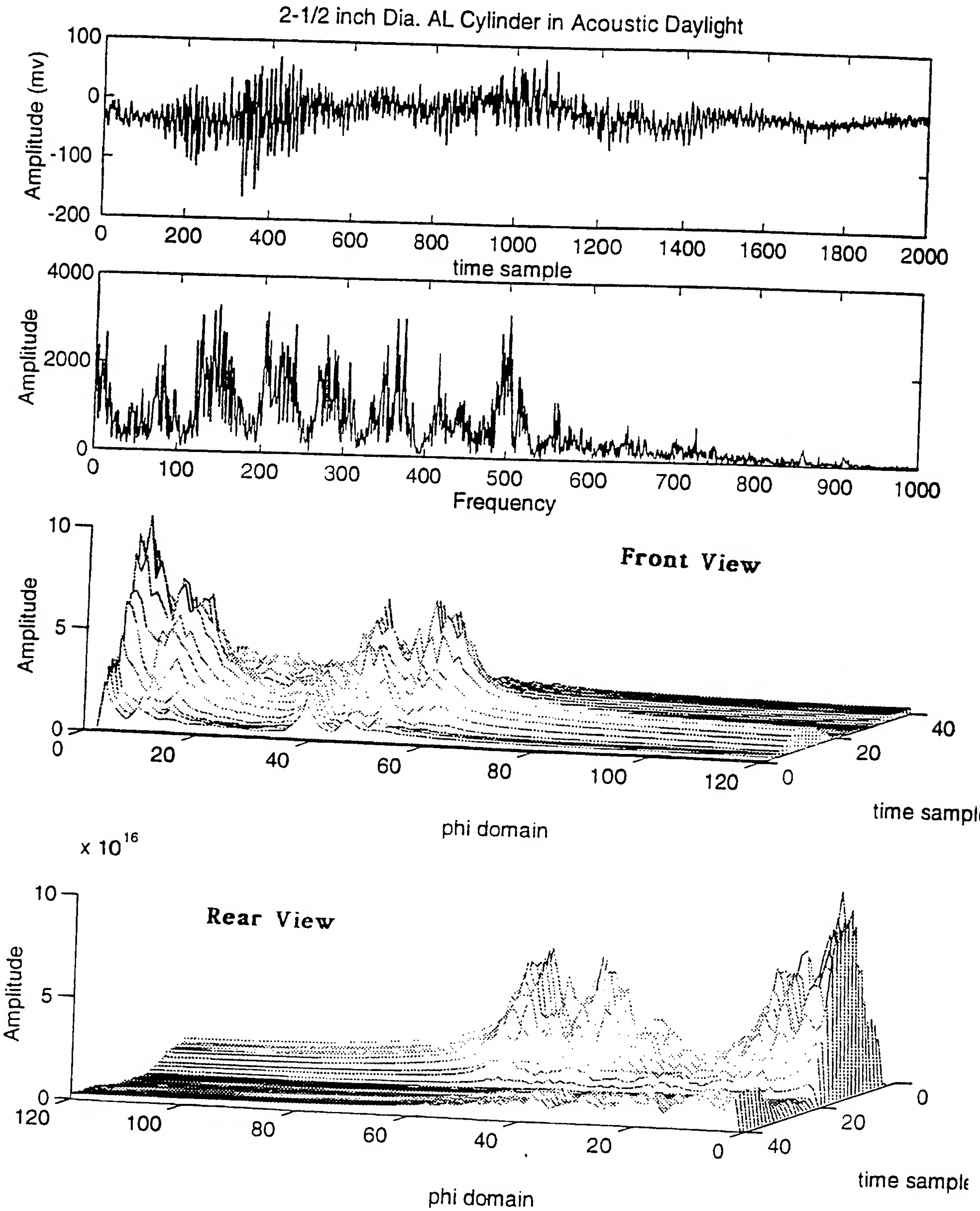

Figure 6. Scattering of a 2.5" Dia. Aluminum Cylinder in Acoustic Background Noise

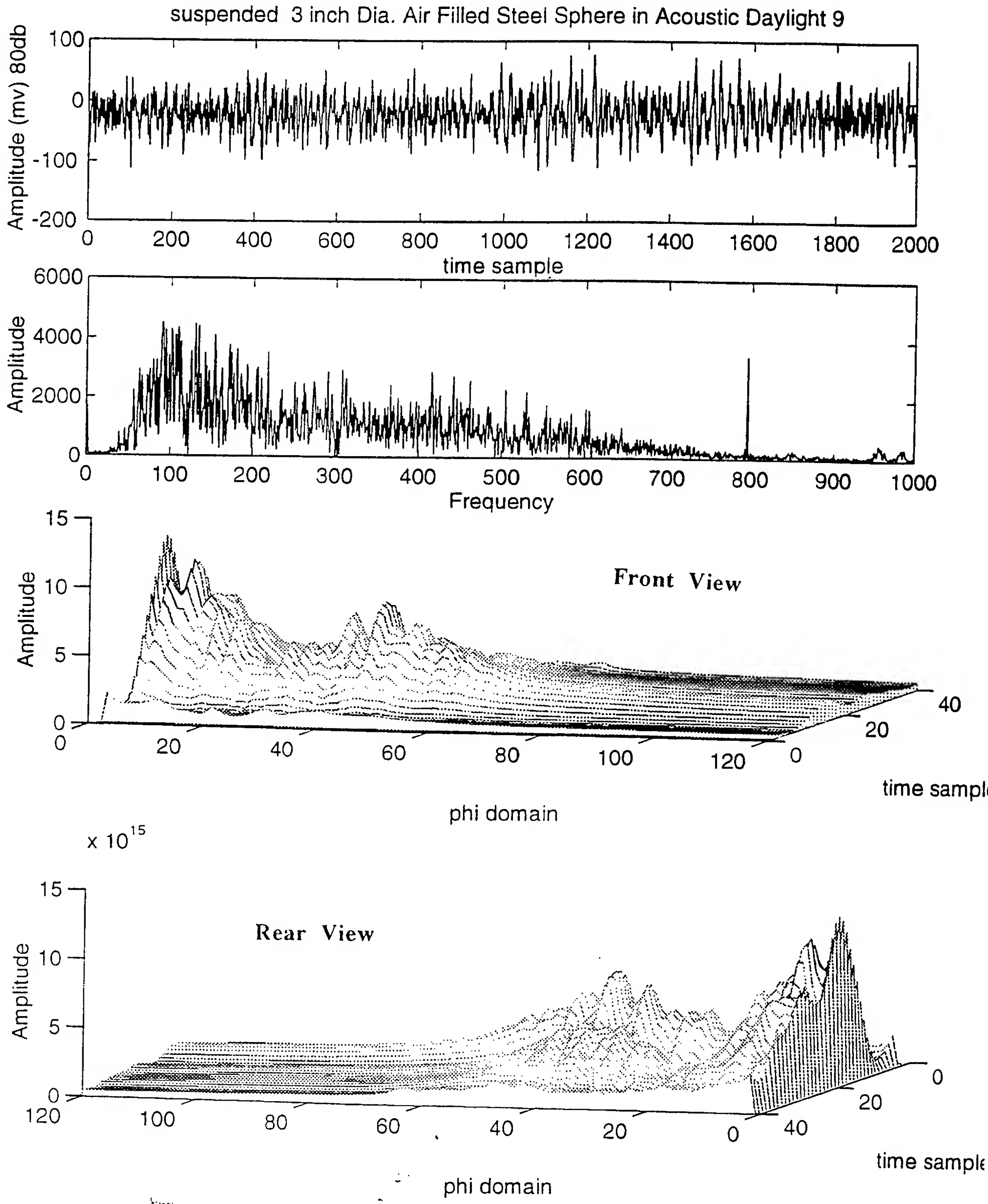

Figure 7. Suspended 3" Air Filled Stainless Steel Sphere in Acoustic Background Noise

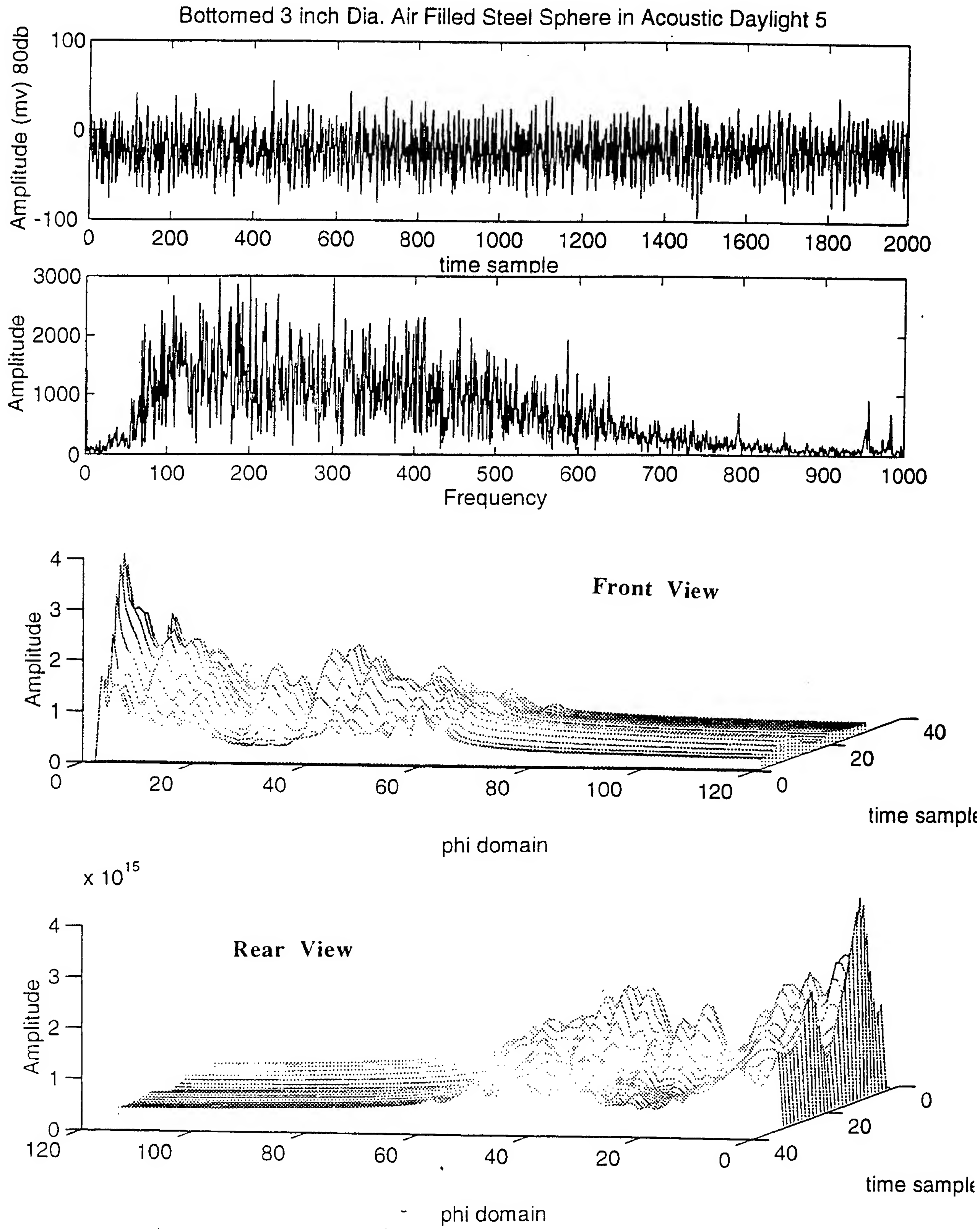

Figure 8. Bottomed 3" Air Filled Stainless Steel Sphere in Acoustic Background Noise

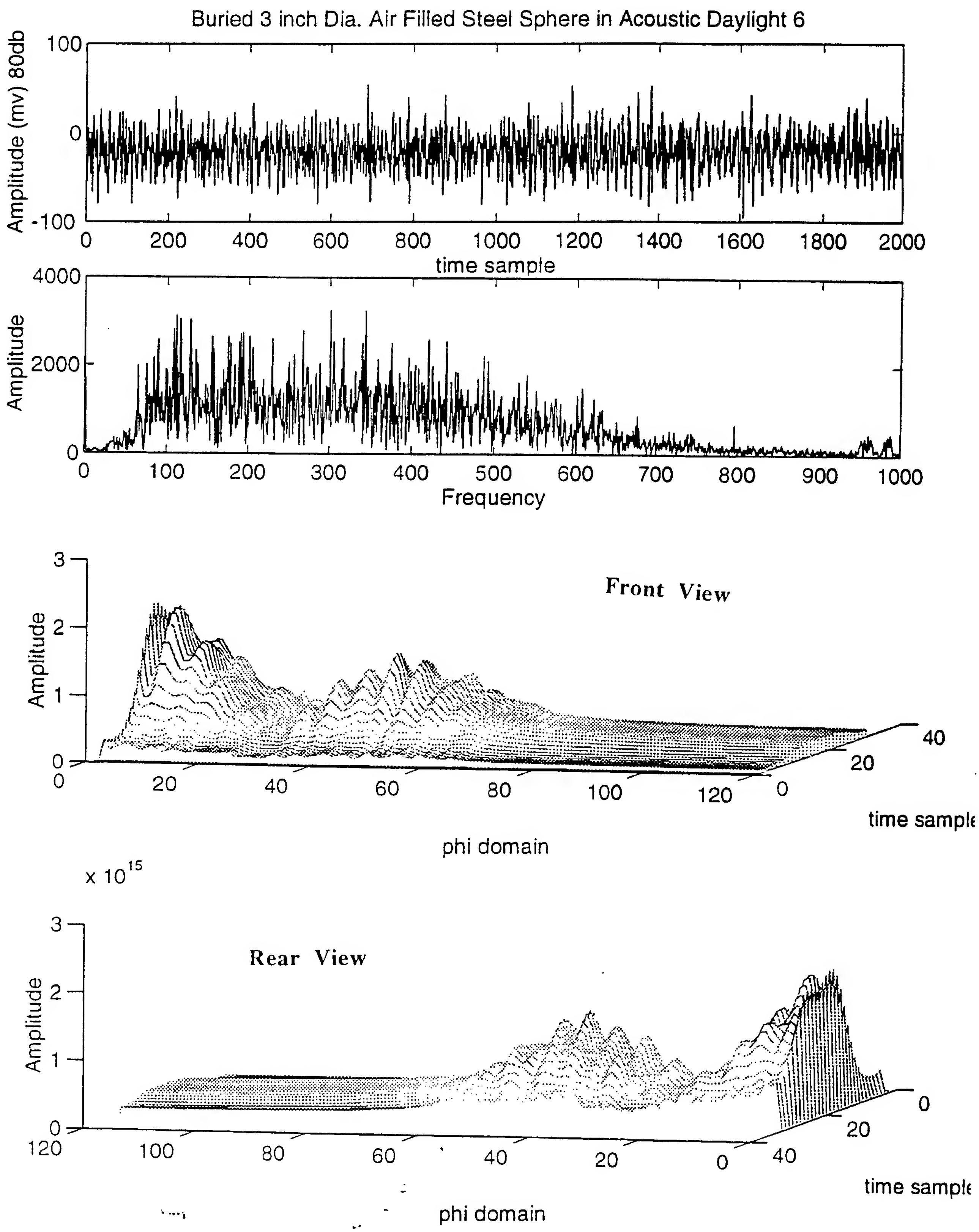

Figure 9. Buried 3" Air Filled Stainless Steel Sphere in Acoustic Background Noise

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